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25. The protease activities (2 to 710 nmol liter^{-1} day^{-1}) of Antarctic isolates exposed to diatom detritus in this study accurately represented the dynamic range of protease activities previously observed for natural assemblages in different sectors of the Southern Ocean from 1991 to 1994 (37 to 1200 nmol liter^{-1} day^{-1}).
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Supporting Online Material

www.sciencemag.org/cgi/content/full/298/5600/1980/DC1

Materials and Methods

Fig. S1

12 July 2002; accepted 31 October 2002

Olmec Origins of Mesoamerican Writing

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A cylinder seal and carved greenstone plaque bearing glyphs dating to ~650 B.C. have been uncovered near the Olmec center of La Venta in Tabasco, Mexico. These artifacts, which predate others containing writing, reveal that the key aspects of the Mesoamerican scripts were present in Olmec writing: the combination of pictographic and glyphic elements to represent speech; the use of the sacred 260-day calendar; and the connection between writing, the calendar, and kingship. They imply that Mesoamerican writing originated in the La Venta polity.

Our excavations at San Andrés, located 5 km northeast of the Olmec center of La Venta, produced a cylinder seal and a greenstone plaque with glyphs dating to ~650 B.C., indicating that writing and the calendar originated in the Mexican Gulf Coast region together with other elements central to Mesoamerican civilization. By the Late Formative period (400 B.C. to A.D. 200), three related hieroglyphic scripts and an associated calendrical system had appeared in three different geographic areas (*1*, *2*) (Fig. 1): the Mayan script extending from the Yucatan Peninsula to the Pacific slope of Guatemala and El Salvador, the Isthmian script extending from the Mexican Gulf Coast through the Isthmus of Tehuantepec, and the Oaxacan script of the Valley of Oaxaca, Mexico. These three Late Formative writing and calendrical systems have close similarities, indicating that they probably developed from a common ancestral script (*3*, *4*) during the preceding Middle Formative period (~900 to 400 B.C.).

Before the discovery of glyphs at San Andrés, the earliest examples of writing and calendrics were attributed to Monument 3 from the Valley of Oaxaca site of San José Mogote (*2*). Monument 3 depicts a slain captive with two glyphs inscribed below the body, probably giving the calendrical name of the victim based on his day of birth in the 260-day sacred Calendar Round (Fig. 1). Monument 3 was originally assigned an age of 600 to 500 B.C., but archaeological, iconographic, and linguistic analyses suggest that Monument 3 dates between 300 B.C. and A.D. 200 (*3*, *5*, *6*). San José Mogote Monument 3 would be contemporaneous with similar, Late Formative monuments depicting glyphs associated with defeated capitals and slain captives from the nearby site of Monte Albán.

San Andrés (Fig. 1) was a subsidiary elite Olmec site within La Venta's sociopolitical network, which encompassed a system of dense settlement along the river levees of the Tabascan coastal plain (*7*). La Venta, with its monumental architecture covering 200 ha, was the preeminent center in Mesoamerica during the Middle Formative period, with influence extending from Central Mexico to El Salvador (*8*, *9*). Excavations at San Andrés in 1997 and 1998 (*10*) yielded a rare sample of primary Olmec living debris: floors, hearths, pits, and midden deposits including well-preserved refuse from festival and feasting activities. This refuse contained human and animal bone, oversized beverage preparation and food serving vessels, large hollow figurines, and a ceramic cylinder seal and engraved greenstone plaque fragments yielding evidence of writing and calendrics.

Charcoal from near the base of the stratigraphic unit that contained the seal and greenstone plaque fragments produced a date of 2490 ±40 radiocarbon years before the present (yr B.P.) (Beta-122241), or a calibrated 2σ calendar date of 792 to 409 B.C. (cal B.C.) with an intercept date of 636 cal B.C. (*10*). Charcoal from two strata above the deposit with the seal and plaque fragments produced a date of 2340 ±90 yr B.P. (Beta-112668), or a calibrated 2σ calendar date of 764 to 182 cal B.C. (intercept date of 398 cal B.C.) (*10*). These dates have large calibration error margins because of the nature of the radiocarbon calibration curve during this time period. The dates are supplemented by a ceramic chronology from San Andrés's well-stratified midden deposits. Excavations at San Andrés uncovered two distinct strata containing ceramics assigned to the Early Franco ceramic phase, which spans the period from 700 to 500 cal B.C. The seal, greenstone plaque fragments, and 636 cal B.C. radiocarbon date come from the lower stratum. Thus, the radiocarbon dating and the ceramic chronology both indicate that the seal and greenstone plaque fragments date to approximately 650 cal B.C.

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The San Andrés seal was probably made within the La Venta polity. Its paste is similar to other ceramics at San Andrés, including a second cylinder seal. Two cylinder seals were also found at La Venta (*11*). Cylinder seals were a rare but integral part of the ceramic inventory within the La Venta cultural sphere.

The San Andrés seal (Fig. 2) provides evidence for the initial stages of logographic writing in the Middle Formative period on the basis of comparisons with Late Formative to Early Classic period Mesoamerican conventions, specifically speech scrolls, cartouche encircling day signs, and paired glyphs composed of grouped elements including affixes and dots as numerals (Fig. 3). The seal depicts two speech scrolls that emanate from the beak of a bird and terminate in two columns of grouped glyphic elements. One scroll ends in a "U" glyph with scroll and bracket elements above (Fig. 3A). The other ends in a glyph containing the "U" and the double merlon motif encircled in a cartouche, also with the scroll and brackets above (Fig. 3H). The "U" element is a common symbol in Middle Formative iconography and early inscriptions (*12*). The scroll and bracket motifs are similar to glyph affixes (prefixes) in the early Mayan, Isthmian, and Oaxacan scripts (Fig. 3, Q to V). The convention of the cartouche demarcating day signs is characteristic of Mesoamerican writing systems. The three dots to the left of the cartouche are similar to the use of dots to represent numerals adjacent to day or month signs. Speech scrolls occur on early Late Formative (~300 B.C.) monuments from Monte Albán and Kaminaljuyú (*13*) but without associated glyphs. The speech scrolls on the San Andrés seal (Fig. 2) represent speech pictographically and signify that the signs they encompass represent words to be spoken as opposed to iconography.

A green serpentine statuette (Fig. 4) (*14*), possibly from La Blanca (*15*) on the Pacific Coast of Guatemala (Fig. 1), with a message similar to that of the San Andrés seal, supports the interpretation of the San Andrés glyphic elements as logographs, i.e., words or concepts. It also provides a connection with an Olmec ruler. The statuette depicts a Young Lord, probably a ruler or his deified ancestor. At his left elbow is a personified form of a bird, denoted by a beak and wings, and, as in the San Andrés seal, a "U" glyph comes out of the "bird's" mouth, indicating that the "U" is spoken (Fig. 4). This bird is one manifestation of the ruler; several Middle Formative sculptures depict a ruler wearing the same winglike cape, which is sometimes feathered (*14*). On his right hand, the Young Lord displays a glyphic element, including the "U" and three dots, similar to the elements in the cartouche on the San Andrés seal (compare Fig. 3, H and I). The San Andrés seal can, therefore, be interpreted as a tool for printing a royal message, probably on perishable materials such as cloth, bark paper, or the human body.

Late Middle Formative elites at the Isthmian site of Chiapa de Corzo preserved both the printing technique and the motifs. A high-status grave from Chiapa de Corzo (*16–18*) contained ceramic stamps with elements re-

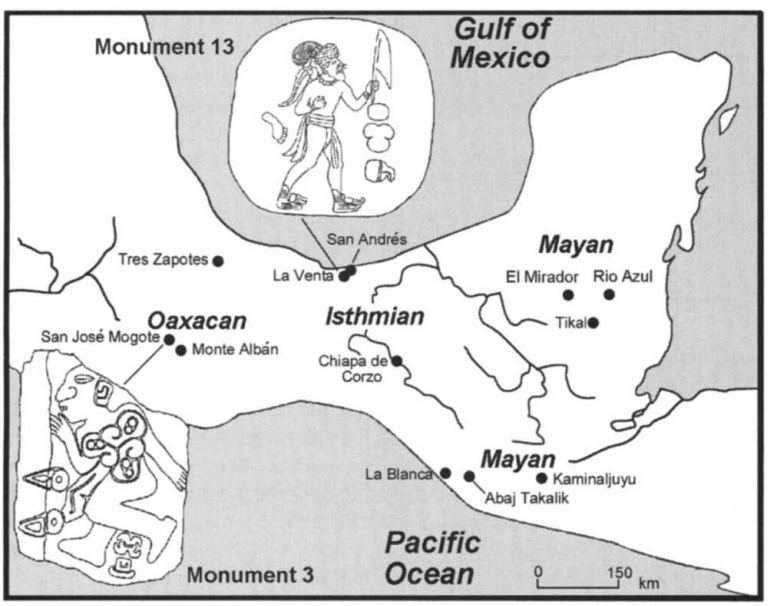

Fig. 1. Map showing Mesoamerican archaeological sites; early monuments with glyphs; and the geographic distribution of the Isthmian, Mayan, and Oaxacan scripts.

Fig. 2. Photograph (**left**) and rollout drawing (**right**) of the cylinder seal from San Andrés, La Venta, Tabasco, Mexico. Scale bar in cm.

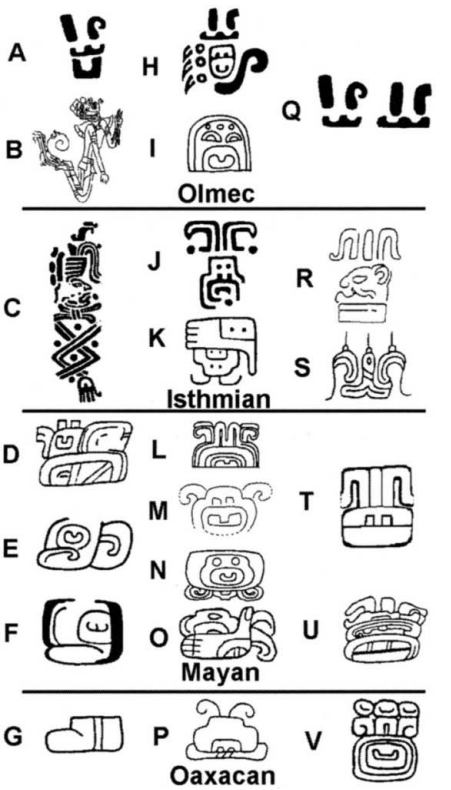

Fig. 3. Comparisons between Isthmian, Mayan, and Oaxacan glyphs and the San Andrés cylinder seal: "U" glyph (left column), "U" and double merlon motif encircled in a cartouche (ajaw glyph) (center column), and scroll glyph prefixes (right column). (**A**) San Andrés "U" glyph. (**B**) Bird impersonator from the Young Lord statuette (see Fig. 4). (**C**) Chiapa de Corzo ceramic cylinder seal from Burial 115 (*16*). (**D**) Dumbarton Oaks jade celt, A.D. 150 (*24*). (**E**) Leiden Plaque, A.D. 320 (*3*). (**F**) Ixtelha cave (*3*). (**G**) Monte Albán Stela 15 (*3*). (**H**) San Andrés "3 Ajaw." (**I**) Young Lord statuette (*14*). (**J**) Chiapa de Corzo flat stamp from Burial 115 (*16*). (**K**) La Mojarra Stela 1, mid-2nd century A.D. (*3*). (**L**) Abaj Takalik, Stela 3, Late Formative period (*25*). (**M**) El Mirador potsherd, Late Formative period (*23, 26*). (**N**) Ajaw glyph, Tikal, Stela 31, A.D. 445 (*21*). (**O**) Ajaw-in-hand glyph, probably from Río Azul (*3*). (**P**) Monte Albán, Lápida J-13 (*21*). (**Q**) San Andrés scroll and bracket elements. (**R**) Tres Zapotes Stela C Initial Series Introductory Glyph, 32 B.C. (*21*). (**S**) La Mojarra Stela 1 (*21*). (**T**) Abaj Takalik Stela 2, 1st or 2nd century B.C. (*27*). (**U**) Tikal Stela 29, A.D. 292 (*21*). (**V**) Monte Albán, South Platform, A.D. 300 to 600 (*28*).

sembling the San Andrés cartouched glyph (Fig. 3J) along with a representational depiction of the ruler (Fig. 3C) shown speaking and associated with the "U" similar to that on the Young Lord statuette (Fig. 3B). The San Andrés cartouched glyphic element also resembles later glyphic elements from Oaxaca (Fig. 3P) and from the La Mojarra stela (Fig. 3K).

The San Andrés cartouched glyphic element is particularly close to early Mayan glyphs representing the day sign *ajaw* (*19*) (Fig. 3, L to O). On the basis of comparisons with these Late Formative and Classic period Mayan glyphs, we interpret the cartouched glyphic element containing the Olmec "U" and double merlon motif with the three associated dots (Fig. 3H) as the calendrical date "3 Ajaw" in the sacred 260-day Mesoamerican calendar.

The word "ajaw" is both a calendrical day name and the word for "king" in the Mayan script. The Late Formative lowland Maya incorporated the "U," the scroll superfix, and a segment of the bracket (Fig. 3A) into their earliest glyphs for the title "ajaw" or "king" (Fig. 3D). The earliest glyphs representing the verb "to seat a king" also contain the "U" and scroll (Fig. 3E) or bracket (Fig. 3F). The "U" and bracket motifs on the San Andrés seal (Fig. 3A) may therefore signify the word "king." Thus, the evidence suggests that the inscription on the San Andrés seal might represent the name "King 3 Ajaw," following the Mesoamerican practice of using birth day names as personal names. Regardless of the exact reading, the presence of the 3 Ajaw day name implies the existence of the sacred 260-day Calendar Round at ~650 B.C. and points to its association with rulership. A calendrical date in a Middle Formative context supports the hypothesis that early writing in Mesoamerica began with the association of day signs and numbers (*3*).

Glyphic elements incised on greenstone plaque fragments from the feasting refuse at San Andrés provide evidence for writing in a second medium, strengthening the argument that the writing system was indigenous to San Andrés and the La Venta polity. The La Venta Olmec distinguished themselves from their predecessors by their focus on greenstone as a precious medium (*14*), and their artisans had a long tradition of incising the stone. The plaque fragments have two complete glyphs preserved along with two possible partial glyphs. One glyph is a double oval with a dot (Fig. 5A), and the other is an encircled double merlon underscored by two lines (Fig. 5B). A double merlon glyph similar to the San Andrés glyph appears on the sceptre held by the Young Lord (Fig. 4 and Fig. 5E), providing an indirect link between the inscriptions found on the greenstone plaque and the cylinder seal from San Andrés.

Our argument that the San Andrés greenstone plaque signs are glyphs rests on similarities with later Mayan and Isthmian texts. Greenstone is a common medium for early inscriptions, especially in the Maya and Isthmian regions, and the rounded outlines of the San Andrés greenstone plaque glyphs conform to the Mayan glyphs (*20*). The San Andrés double oval glyph bears specific resemblance to glyphs found in later Isthmian texts, especially to one of the glyphs on a ceramic vessel from Chiapa de Corzo (*21*), dated stylistically between 300 and 50 B.C. (Fig. 5C). A glyph on the La Mojarra stela, which bears dates in the mid-2nd century A.D., may be a later version of this glyph (Fig. 5D). Both of the San Andrés glyphs also have subgraphemic elements that occur later in the Mayan script. For example, the double merlon's underscored, stepped elements occur in the Abaj Takalik Stela 2 Initial Series Introductory Glyph (Fig. 3T) and in the Mayan sign for hieroglyphic book. The double oval resembles the Mayan day sign *muluk*, though it lacks the diagnostic two small circles (*20*).

La Venta has two other examples of early writing, probably dating to the last major construction phase between 600 and 400 B.C. (*11*, *22*). Monument 13 (Fig. 1) has a block of three vertical glyphs. Altar 7 features a human face with duckbill mask flanked by a human figure with three round-cornered, rectangular glyphs coming from the mouth (*11*), a technique for representing speech analogous to the scrolls on the San Andrés seal.

Later Mesoamerican groups borrowed heavily from Middle Formative Olmec traditions. Writing and calendrics spread from this central Isthmian region to Western and Eastern Mesoamerica along with new systems of kingship based, in part, on military conquest. Linguistic studies support the hypothesis of the Isthmian region as the origin of the common ancestor. Archaeological sites with evidence for the Isthmian script have the same geographic distribution as the present-day Mije-Soke language. Other Mesoamerican languages include Mije-Soke loan words (*23*) for "to write," "paper," "year," "to count," and "twenty" (denoting the vigesimal numerical system that underlies the 20-day month). In Eastern Mesoamerica, the Maya developed the Olmec prototype into the New World's most elaborate glyphic writing and calendrical system. Writing and the calendar were essential tools of kingship in ancient Mesoamerica. Glyphs imprinted on clothing or the body using cylinder seals, and engraved on greenstone plaque jewelry, were one of the principal means by which high-status individuals conveyed the message of kingship in the context of feasting.

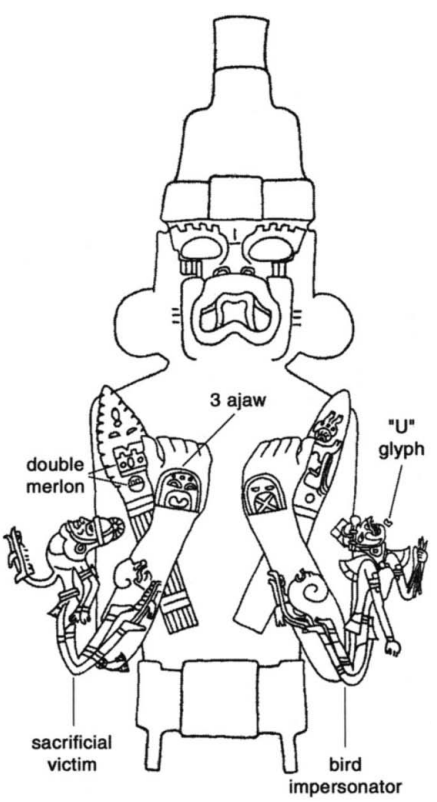

Fig. 4. Torso of Young Lord statuette (*14*).

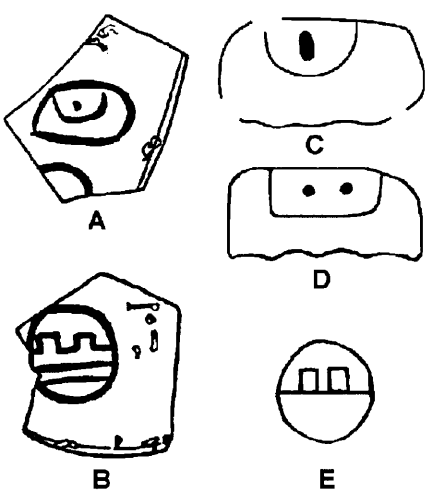

Fig. 5. (**A** and **B**) San Andrés greenstone plaque fragments, probably from high-status jewelry. Glyph in (A), 9.5 mm wide and 5.5 mm high; glyph in (B), 7 mm wide and 9 mm high. (**C**) Chiapa de Corzo potsherd (*29*). (**D**) La Mojarra Stela 1 (*29*). (**E**) Young Lord statuette (*14*).

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Grassland Responses to Global Environmental Changes Suppressed by Elevated CO_2

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Simulated global changes, including warming, increased precipitation, and nitrogen deposition, alone and in concert, increased net primary production (NPP) in the third year of ecosystem-scale manipulations in a California annual grassland. Elevated carbon dioxide also increased NPP, but only as a single-factor treatment. Across all multifactor manipulations, elevated carbon dioxide suppressed root allocation, decreasing the positive effects of increased temperature, precipitation, and nitrogen deposition on NPP. The NPP responses to interacting global changes differed greatly from simple combinations of single-factor responses. These findings indicate the importance of a multifactor experimental approach to understanding ecosystem responses to global change.

Human actions are affecting many aspects of the Earth system. The composition of the atmosphere, the climate, the abundance of invasive species, and the area of managed landscapes have all undergone important changes in the past century. These changes are likely to be even greater in this century (*1*). In almost any setting, realistic global change is decidedly multifactorial. Warming, increased precipitation, increased deposition of N-containing compounds, and increased atmospheric CO_2 are all likely consequences of CO_2 emissions from fossil fuel combustion and land use change (*2*). In the past century, atmospheric CO_2 concentration has increased globally by more than 30% (*2*). Temperature, precipitation, and deposition of biologically available N have increased for large regions (*3–5*). Further increases in the future are almost certain.

Most of the experimental research on ecosystem responses to global change has addressed responses to single global changes, with relatively few studies exploring responses to two or more interacting treatments (*6–8*). Experimental manipulations of both temperature and CO_2 concentration are rare at the ecosystem scale (*9*, *10*), even though elevated CO_2 is a primary driver of climate change (*2*).

Several modeling studies have addressed ecosystem responses to multifactor global changes (*11*, *12*), but the theoretical foundation for predicting ecosystem responses to simultaneous changes in multiple factors is incomplete. For some processes (such as photosynthesis), well-tested mechanistic models support the simulation and interpretation of multifactor responses (*13*). For many other processes, however, including biomass allocation, the timing of seasonal activity, and species replacements, the empirical data are too sparse to support credible models or allow comprehensive hypothesis tests.

Both empirical and modeling studies highlight potential contrasts in responses to single global changes and multiple, interacting global changes. Stimulation of plant growth by elevated CO_2, for example, may be strongest when water is limiting (*14*), when nutrients are abundant (*15*), or when plant species diversity is high (*6*). Simulated ecosystem responses to future global changes depend strongly on such interactions. In many settings, simulated warming increases decomposition more than net primary production (NPP), leading to a loss of carbon (*16*). In others, elevated CO_2 and N deposition tend to increase NPP more than decomposition, leading to carbon storage. In some simulations, the responses of carbon storage to the three factors nearly cancel one another out. In others, changes combine in nonadditive ways, with examples of both suppression and amplification (*11*).

One of the keys to understanding the long-term impacts of multiple global changes on ecosystem function will be experiments on model ecosystems that are amenable to factorial manipulations and respond rapidly. Annual grassland, with a high diversity of small short-lived plants, is an attractive model system for global change experiments. An area of less than 1 m^2 is sufficient for a meaningful global-

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